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COMPARISON OF THE MODE S SYSTEM TO THE AUTOMATED RADAR TERMINAL--ETC(U)
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Comparison of the Mode S System to the Automated Radar Terminal System (ARTS) with Respect to Range and Azimuth Resolution

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July 1982

Interim Report

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16. Abstract <p>A series of flight tests were conducted at the Federal Aviation Administration Technical Center to compare the range and azimuth resolution capabilities of the Mode S (formerly the Discrete Address Beacon System (DABS)), in the Air Traffic Control Radar Beacon System (ATCRBS) mode, to an existing Automated Radar Terminal System (ARTS) III. The minimum achievable range and azimuth separation of two aircraft, without garbling of either aircraft's A-Code, was determined for both systems. The resolution results were compared to positional aircraft separation data, collected concurrently by a precision Range Instrumentation System, to determine the relationship between A-Code garbling and aircraft separation.</p> <p>The flight test results indicate that the 89 percent beacon resolution achieved with the correlated-only Mode S sensor has the best overall resolution in the aircraft separation intervals of 0° to 2° in azimuth and 0 to 10,000 feet in range. The combined correlated and uncorrelated Mode S reports were 80 percent resolved, whereas, the ARTS reports for the same aircraft separation intervals were 62 percent resolved. The minimum achievable range separation, without garbling, was approximately 10,000 feet for both systems. The azimuth separation was 2° for the Mode S system and 3.2° for the ARTS system.</p>			
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	meters	m
yds	yards	0.9	kilometers	km
mi	miles	1.6		
AREA				
sq in	square inches	6.5	square centimeters	cm ²
sq ft	square feet	0.09	square meters	m ²
sq yds	square yards	0.8	square meters	m ²
sq mi	square miles	2.6	square kilometers	km ²
acre	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
cup	teaspoons	5	milliliters	ml
1/2 cup	tablespoons	15	milliliters	ml
qt	fluid ounces	30	milliliters	ml
pint	quarts	0.25	liters	l
gal	gallons	0.47	liters	l
cu ft	gallons	0.86	liters	l
cu yd	gallons	3.8	liters	l
cu ft	cubic feet	0.03	cubic meters	m ³
cu yd	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Mon. Publ. 280, Units of Weight and Measure, Price \$2.25, SO Catalog No. C13.10286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	1.1	miles	mi
km	kilometers	0.6	miles	mi
AREA				
sq cm	square centimeters	0.16	square inches	sq in
sq m	square meters	1.2	square yards	sq yds
ha	hectares (10,000 m ²)	0.4	square miles	sq mi
ha	hectares (10,000 m ²)	2.5	acres	acre
MASS (weight)				
g	grams	0.005	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	cu ft
m ³	cubic meters	1.3	cubic yards	cu yd
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

PURPOSE.

The purpose of this effort was: (1) to compare the range and azimuth resolution capabilities of the Mode S in the Air Traffic Control Radar Beacon System (ATCRBS) mode to a typical Automated Radar Terminal System (ARTS) III; and (2) to determine for both systems the minimum achievable range and azimuth separation of two aircraft without A-Code garbling of either aircraft's report.

BACKGROUND.

The Mode S sensor was designed to provide air traffic control (ATC) surveillance and communications data to the Federal Aviation Administration (FAA) National Airspace System (NAS) consisting of both terminal and en route ATC systems. Concurrent with the acceptance testing of the Mode S, an FAA test and evaluation (T&E) effort was conducted at the FAA Technical Center to determine general baseline performance characteristics. The results of this T&E activity are described in report FAA-RD-80-36, "Discrete Address Beacon System (DABS) Baseline Test and Evaluation" (reference 1).

Subsequently, a program was developed and conducted at the Technical Center to obtain detailed performance characteristics of the Mode S for comparison with the FAA engineering requirements (FAA-ER-240-26) and the performance of existing counterparts of the FAA NAS. Because of the complexity of this program, several specific functions required evaluation and issuance of a formal report. In particular, the Mode S system accuracy function required a series of flight tests to determine the range and azimuth accuracy of each sensor. This was accomplished by a comparison of an aircraft's positional data within each sensor's target report to precise values obtained simultaneously from a instrumentation air-ground tracking system. Another function related to system accuracy is the capability of Mode S to identify and report the position of each of two aircraft that are within close proximity. This function is termed beacon resolution and was not previously tested.

DEFINITION OF BEACON RESOLUTION.

Beacon resolution is defined as the minimum separation between two aircraft that can be obtained while the beacon system still provides one, and only one, legitimate target A-Code for each of the two aircraft. Mode S/ARTS beacon resolution is the topic of this report.

DESCRIPTION OF EQUIPMENT

MODE S.

Mode S is a secondary radar system with both surveillance and communication capabilities and is designed as an evolutionary improvement over the existing ARTS system within the ATC environment. FAA reports FAA-RD-74-189 (reference 2) and FAA-RD-80-41 (reference 3) contain complete functional descriptions of the Mode S system and also indicate several design improvements over existing

surveillance systems. The most significant improvement is the improved aircraft positional determination that results from the use of an antenna monopulse design and associated receiver processing. This aircraft positional data, expressed in slant range and azimuth, are part of a target report that is compiled during each antenna scan, approximately every 4.7 seconds, and is transmitted via telephone lines to remote ATC facilities. The target reports also include the aircraft's A-Code, altitude if available, and are time-marked for future reference.

ARTS III.

The ARTS III is a secondary radar system that provides surveillance capabilities only. The ARTS converts beacon video, derived from an Air Traffic Control Beacon Interrogator (ATCBI)-4, into digital target reports once each antenna scan. These reports are forwarded to the ARTS tracker and provide positional data, A-Code, and altitude if available, to the air traffic controller. These reports are also time-marked for future reference.

The modular design of the ARTS allows for a number of system configurations. The configuration used for comparative beacon resolution testing was comprised of the ATCBI-4, a Beacon Data Acquisition System (BDAS), and an input/output processor (IOP). The ATCBI-4 was collocated in the same building as the Mode S sensor. The Mode S beacon antenna, a 5-foot ATCRBS antenna, was used for both the Mode S sensor and the ARTS-III, thereby, giving both systems the same geographical location.

NIKE.

The Nike-Hercules is an accurate radar tracking system capable of tracking two targets simultaneously. The system utilizes a target tracking radar (TTR) to track one target, and a missile tracking radar (MTR) to track the other target. The Nike provides accurate positional data at a rate of 10 reports each second, and each report is time-marked. Nike was used during all flight tests in order that the slant range and angular displacement between the two aircraft could be accurately determined. Detailed capabilities of the Nike tracking system are listed in report FAA-NA-79-32, "NAFEC Range Instrumentation System" (reference 4).

TEST METHODOLOGY

ATCRBS VERSUS ATCRBS MODE.

The capability and necessity of the Mode S sensor to report aircraft positional data in two separate modes (Mode S and ATCRBS) indicates that resolution testing was desirable in the Mode S versus Mode S, Mode S versus ATCRBS, and ATCRBS versus ATCRBS configurations. However, Mode S targets are always resolved (identifiable) due to the discrete address characteristic of the Mode S system. The ATCRBS targets are always resolved from Mode S targets due to the fact that they are interrogated during different time periods. This was confirmed during a series of informal flight tests conducted in July 1980. Two Modes S transponders and an ATCRBS transponder were mounted in the same aircraft and flight tested. The test results indicated excellent performance from all transponders in that the Mode S roll-call and ATCRBS interrogations are scheduled in different time periods by

the Mode S sensor. Hence, the garbling condition which can degrade resolution performance is not a problem for aircraft equipped with Mode S transponders. Therefore, this report is concerned with obtaining and comparing system beacon resolution while the Mode S sensor is operating in the ATCRBS mode only.

MODE S DISSEMINATION OPTIONS.

Data processed by the Mode S sensor can be transmitted to ATC facilities in either of two dissemination options: (1) correlated-only target reports, or (2) correlated and uncorrelated target reports. Correlated target reports are those reports which are correlated to a surveillance track. Conversely, uncorrelated target reports are those reports that do not correlate to a surveillance track. Typically, correlated-only target reports are disseminated to terminal ATC facilities, while correlated and uncorrelated target reports are typically disseminated to en route ATC facilities. The Mode S sensor was designed to disseminate either option. The dissemination buffers for both correlated-only, and correlated and uncorrelated target reports were recorded. The beacon resolution results corresponding to these dissemination options were compared to resolution results of the ARTS.

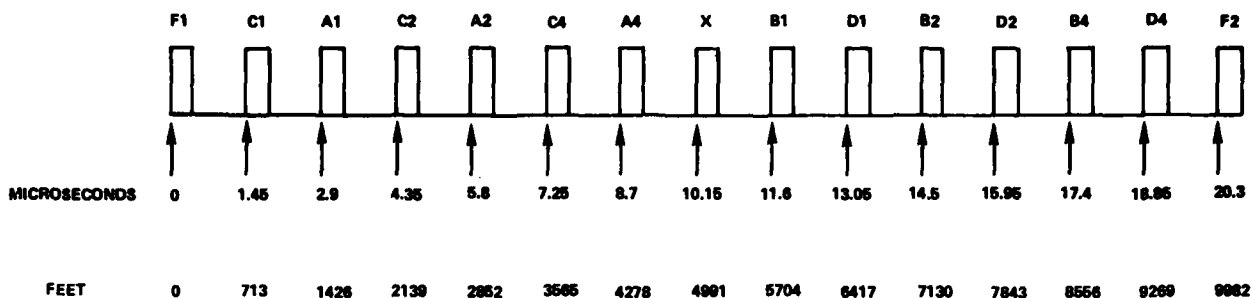
A-CODE SELECTION.

It is known that the determination of beacon resolution performance is dependent upon two specific A-Codes that interfere or overlap with each other. Consequently, it was originally planned to test with more than one set of beacon codes. However, only one pair of codes was used to minimize flight time since six test flights were needed to obtain a suitable number of data samples on both the Mode S and ARTS systems. The two selected codes, 0251 and 0252, which were made available by the local ATC facility for all tests, characterized a normal field-type environment. Beacon codes, which contain predominantly all zero bits or predominantly all one bits, were avoided. By using the same pair of codes for all tests, the Mode S and ARTS systems could be directly compared.

GARBLING CONSIDERATIONS.

The main contribution to decreased system beacon resolution is a phenomenon called garbling. Garbling is caused when two radiofrequency (RF) signals, while propagating through space, overlap or interfere with each other. This phenomenon occurs when two aircraft are in close proximity and their beacon transponders reply to the same ground interrogation at the same, or almost the same time.

A-CODE BIT ANALYSIS. The ATCRBS reply signal format characteristics, which are defined in the United States ATCRBS National Standard, are illustrated in figure 1. The total time from the leading edge of the F1 framing pulse to the leading edge of the F2 framing pulse is 20.3 ± 0.1 microsecond, regardless of the A-Code being considered. Each A-Code contains 12 bits embedded between the F1 and F2 pulses. Since a total interrogation to reply time of 1 microsecond equates to 492 feet of range, the 20.3 microsecond time span equates to nearly 10,000 feet. The time between the leading edges of successive pulses in the reply train is 1.45 microseconds or about 713 feet of range. This time is comprised of 0.45 microseconds (221 feet) for the actual pulse width, with the remaining 1 microsecond (492 feet) being the time between pulses, which is known as the interleaved period.



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FIGURE 1. ATCRBS REPLY SIGNAL FORMAT

A possible A-Code garbling condition occurs between two aircraft when two or more bits overlap (one from each aircraft). The actual bits that conflict can consist of both bits unset, both bits set, or only one of the two bits set. The actual slant range separation of the two aircraft determines the number of potential bit conflicts that prevail. The case where both bits are unset should not present a problem since no energy exists. However, conflicts where one or both bits are set can cause an erroneous A-Code to be processed.

TIME SYNCHRONIZATION. In order to determine and analyze beacon resolution results, it was necessary that every target report (Mode S, ARTS, and Nike) be accurately time-marked. The positional data included in the Mode S and ARTS target reports were not used to determine the slant range between the two aircraft, only the Mode S and ARTS time information were used. The Nike position data were time correlated to the Mode S and ARTS time information. Consequently, the Nike positional data were used to determine the slant range and azimuth between the two aircraft.

Due to these considerations, it was necessary that the Mode S, ARTS, and Nike systems be time synchronized to a common time standard. The time reference used for time-synchronization during all testing was the National Bureau of Standard's transmissions from station WWVB at Boulder, Colorado.

The Mode S and Nike systems are automatically time-synchronized to WWVB. However, the ARTS system did not have this capability and was manually time-synchronized to WWVB before every test. Manual synchronization was accomplished by receiving a time mark over the telephone and manually setting the ARTS clock to the correct time at the instant. While some error is obvious due to manual synchronization, it was determined that the overall time synchronization error was always less than 0.5 second.

Time synchronization is important because time is what is used to determine each aircraft's position and, consequently, the slant range between the aircraft. Considering that the difference in speed of the two aircraft was never more than 50 knots, the 0.5-second time error would amount to only 42 feet slant range error. This error (42 feet) is not considered a major factor while determining beacon resolution.

TEST CONFIGURATION

FUNCTIONAL RELATIONSHIP BETWEEN MODE S, ARTS, AND NIKE.

Figure 2 depicts the functional relationship between the Mode S sensor, the ARTS system, and the Nike-Hercules tracking system. Data recorded at the Mode S sensor's Data Extraction Subsystem (DEX), the ARTS's IOP, and the Nike tracking system were time correlated using WWVB time synchronization, as previously mentioned.

TRANSPONDERS.

The two transponders used in both test aircraft for all tests were: (1) An ATCRBS transponder capable of responding to the Mode S (ATCRBS mode) or ARTS interrogations, and (2) an X-Band transponder designed solely for use with the Nike tracking system.

FLIGHTPATH CONSIDERATIONS AND DETERMINATION.

Aircraft resolution data were collected by the Mode S sensor, in the ATCRBS mode, for three test flights for comparison with precise positional data obtained concurrently by the Nike tracking system. Similarly, three additional test flights were conducted collecting ARTS resolution data, which were also compared to the concurrent precise Nike positional data.

The flightpaths, chosen for all flight testing, were based on the Nike tracking capabilities. Although maximum precision was not required, the flightpaths were limited to that area which produced the optimum accuracy from the Nike tracker. The headings of the radial flightpaths were selected to preclude any beam obstructions between the aircraft and the Nike location due to nearby adjacent buildings or any other obstructions.

Figure 3 illustrates the approximate radial flightpaths of both test aircraft. The outbound segments of the flightpath commenced about 5 nautical miles (nmi) south-east of Atlantic City's very high frequency (VHF) omnidirectional radio range (VOR) along a 110° radial. Initially, both aircraft proceeded along the radial when the overtaking aircraft was directed to overtake the target aircraft at about the halfway point (25 nmi) and then continue along the radial until reaching the 45 nmi turning point. At this point, the overtaking aircraft was about 2 nmi beyond the target aircraft. However, some aircraft range separation data beyond 2 nmi were recorded. Approximate air speed and altitude were 200 knots and 10,000 feet. The inbound segments of the flightpath were accomplished in the same manner as the outbound segments. Each of the six test flights consisted of several inbound and outbound segments.

This flight plan was utilized for all test flights with the target aircraft flying a 110° radial and the overtaking aircraft flying at either 110°, 111°, or 112°, as illustrated in figure 4. These flights yielded a reasonable distribution of aircraft separation including some azimuth separation data beyond 2°. The data extending beyond 2° azimuth separation and 2 nmi range separation was due to the two pilot's inability to fly exact radials. These data points were expected and were used in the analysis. The separation generally ranged from 0° to 2° in azimuth and 0 to 10,000 feet in slant range. Both aircraft were always separated in altitude by approximately 500 feet and had A-Codes (0251 and 0252).

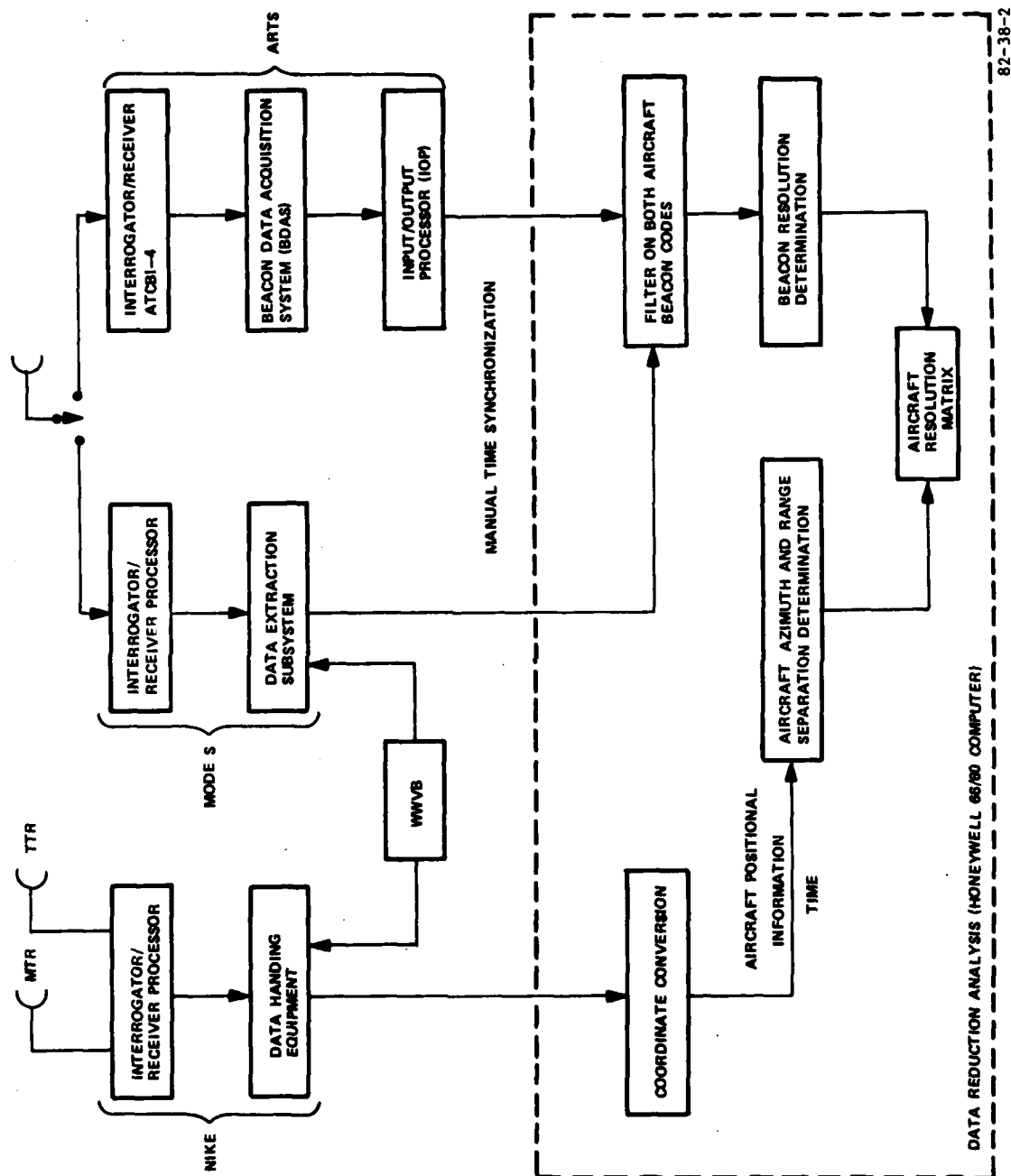


FIGURE 2. FUNCTIONAL RELATIONSHIP AMONG THE MODE S SENSOR, THE ARTS III, AND THE NIKE TRACKING SYSTEM

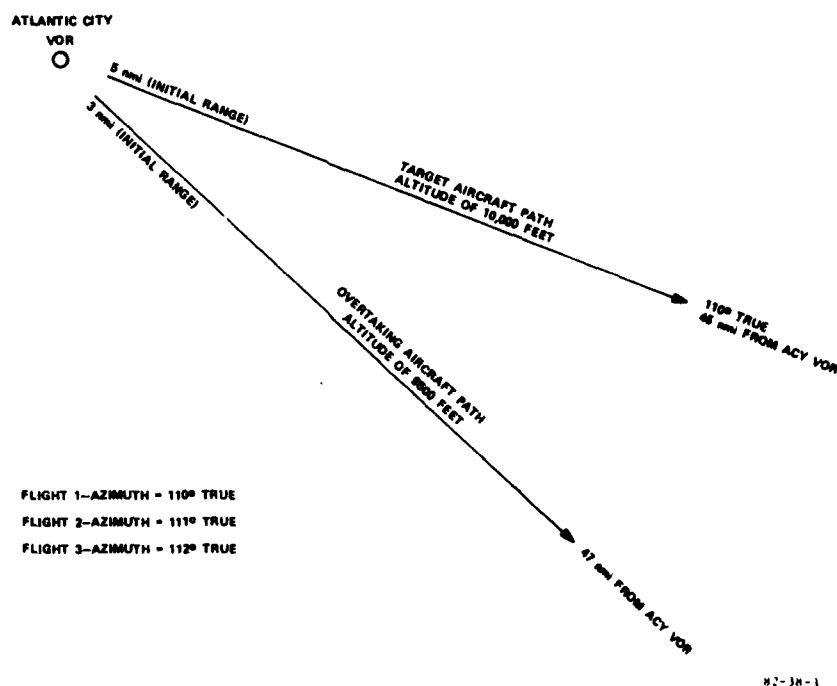


FIGURE 3. RADIAL FLIGHTPATHS OF EACH AIRCRAFT

DATA REDUCTION PROCEDURES

Data reduction was accomplished utilizing the Technical Center's Honeywell 66/60 general purpose computer. Specific data reduction programs were developed by the Range, Programming and Analysis Branch, ACT-750, to accomplish the following procedures:

1. The Mode S and ARTS data extraction tapes were filtered for A-Codes 0251 and 0252. The output, which is recorded onto a filter tape, consisted of all target reports containing the specified A-Codes.
2. Based on the filter tape output, the number of reports for each aircraft were tabulated to determine, for each antenna revolution, the number of correct reports that were received. From the basic resolved definition of one, and only one, correct beacon A-Code for each aircraft, a tabulation was made of the number of scans that produced resolved versus unresolved conditions.

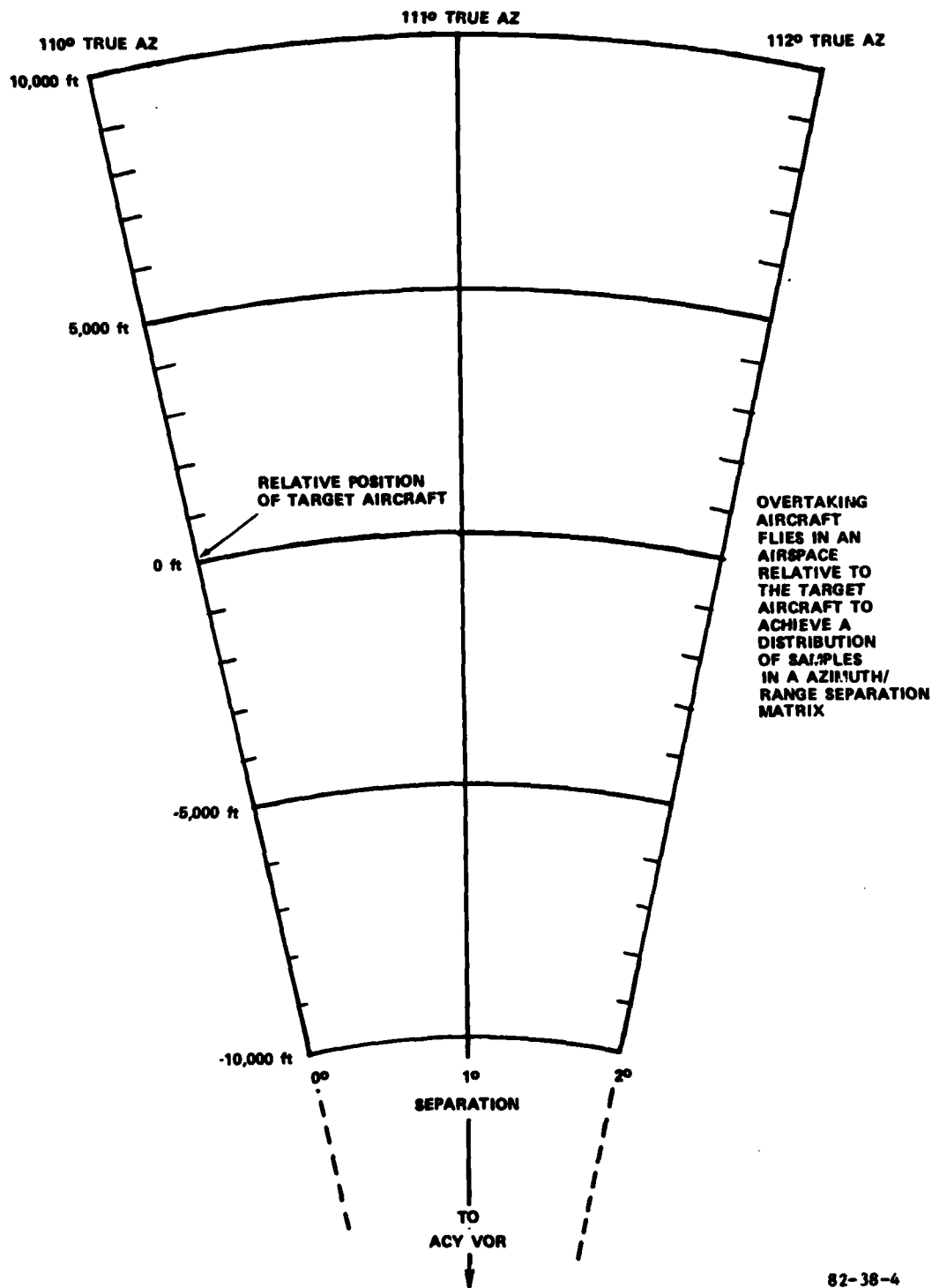


FIGURE 4. RESOLUTION TEST FLIGHT: AIRCRAFT RANGE AND AZIMUTH SEPARATION DATA DISTRIBUTION

3. The Nike data extraction tapes were scanned using the synchronized time of each aircraft's target report from both the Mode S and ARTS extractor tapes. The Nike positional data for both aircraft were geometrically translated to the Mode S/ARTS antenna coordinate system. The range and azimuth aircraft separation was then computed from the translated Nike positional data.

4. From the tabulation of resolved versus unresolved conditions, analysis were performed in specific range and azimuth separation groupings to illustrate the resolution capabilities of the Mode S sensor for both dissemination options as well as for the ARTS system.

5. Special computer programs were developed to illustrate graphically the test results for selected range and azimuth aircraft separation intervals. The data from these separation intervals were also used for the analytical comparison of each system's beacon resolution capabilities.

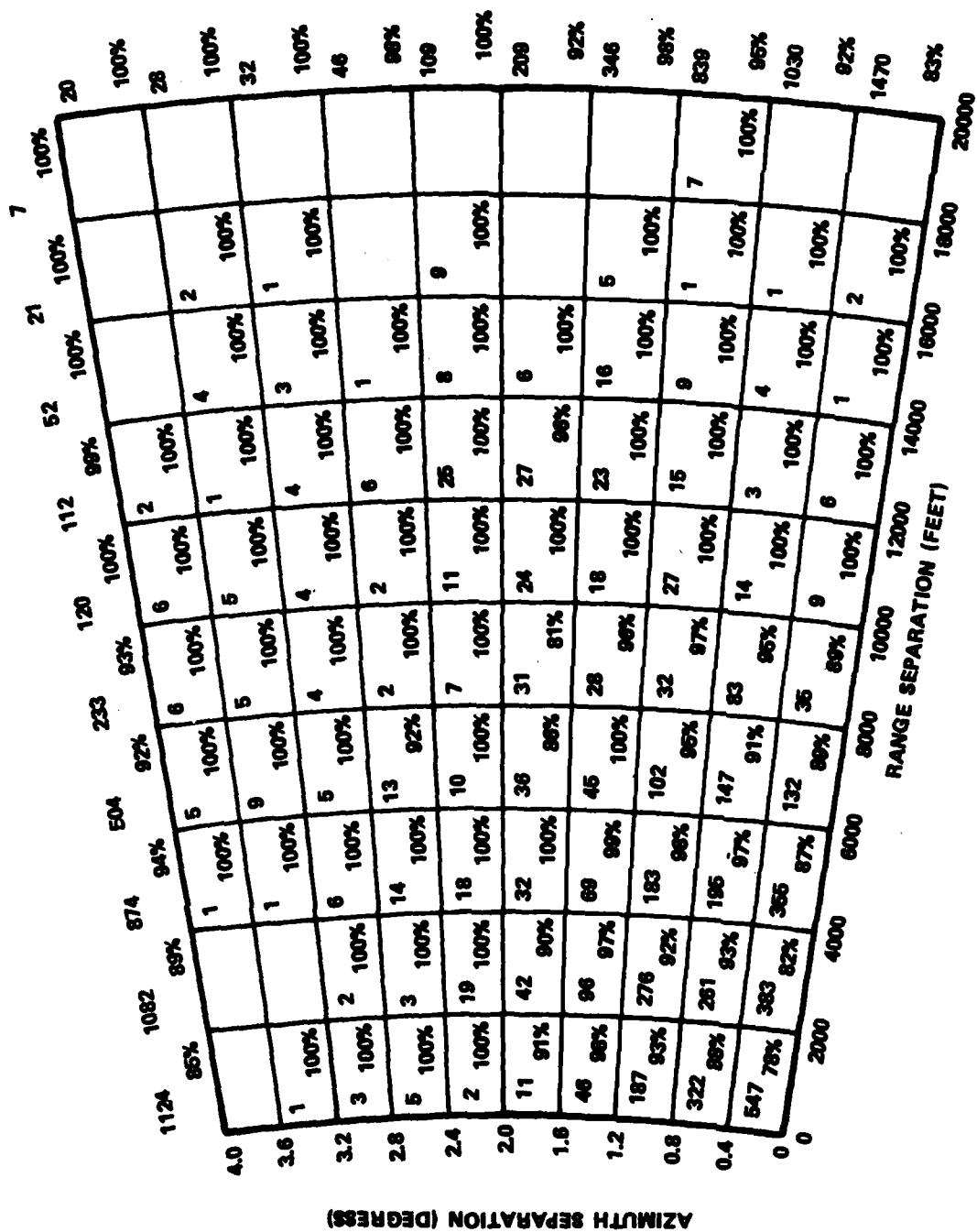
TEST RESULTS AND ANALYSIS

MINIMUM RANGE AND AZIMUTH SEPARATION WITHOUT GARBLING.

The beacon A-Codes from two aircraft are considered resolved when the 12 bits from both reports are interpreted correctly, thereby, returning the proper four-character octal code from each aircraft. If the same code appears in two or more reports or if either or both codes are improperly decoded, then an unresolved situation exists for that antenna scan.

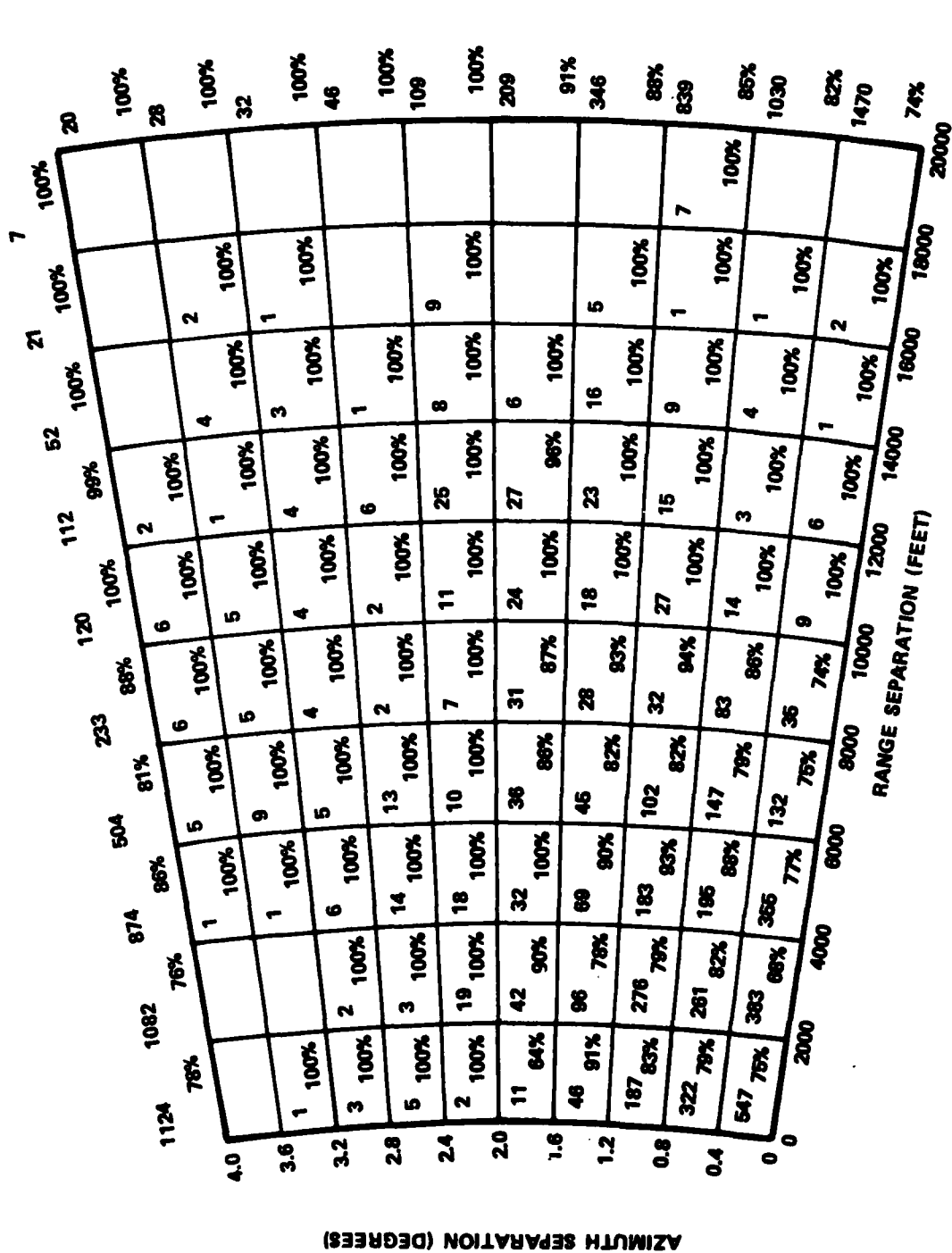
Figure 5 illustrates the resolution results of correlated-only reports disseminated by the Mode S sensor from the total samples available for azimuth separation intervals every 0.4° , from 0° to 4° , and range separation intervals every 2,000 feet, from 0 to 20,000 feet, yielding a 10 X 10-foot cell resolution matrix. This matrix contains the total number of samples available and the percentage of correlated-only reports resolved for each of the 100 cells. In addition, the values above the matrix represent the total number of samples and the percent resolution for the 10 range separation intervals. The values on the right side of the matrix represent the total number of samples and the percent resolution for the 10 azimuth separation intervals. Figure 6 illustrates the resolution results for all correlated and uncorrelated reports disseminated by the Mode S sensor. Figure 7 illustrates the resolution results for the target reports processed from the ARTS III.

A cursory examination of figures 5 and 6 indicate that the Mode S target reports approach 100 percent resolution when the two aircraft are separated by approximately 10,000 feet in range and/or 2° in azimuth. However, figure 7 indicates that the ARTS reports do not approach 100 percent resolution until the two aircraft are separated by approximately 10,000 feet in range and/or about 3.2° in azimuth. The 10,000-foot range separation is required to insure that the two beacon A-Codes will not overlap and interfere (garble). The beacon A-Code, from the leading edge of F1 to the trailing edge of the F2 pulse, is 20.75 microseconds in time duration or approximately 10,200 feet (see figure 1). The Mode S system does not require as much azimuth separation as the ARTS (2.0° versus 3.2°) due to the monopulse techniques utilized by the Mode S receiver/processor.



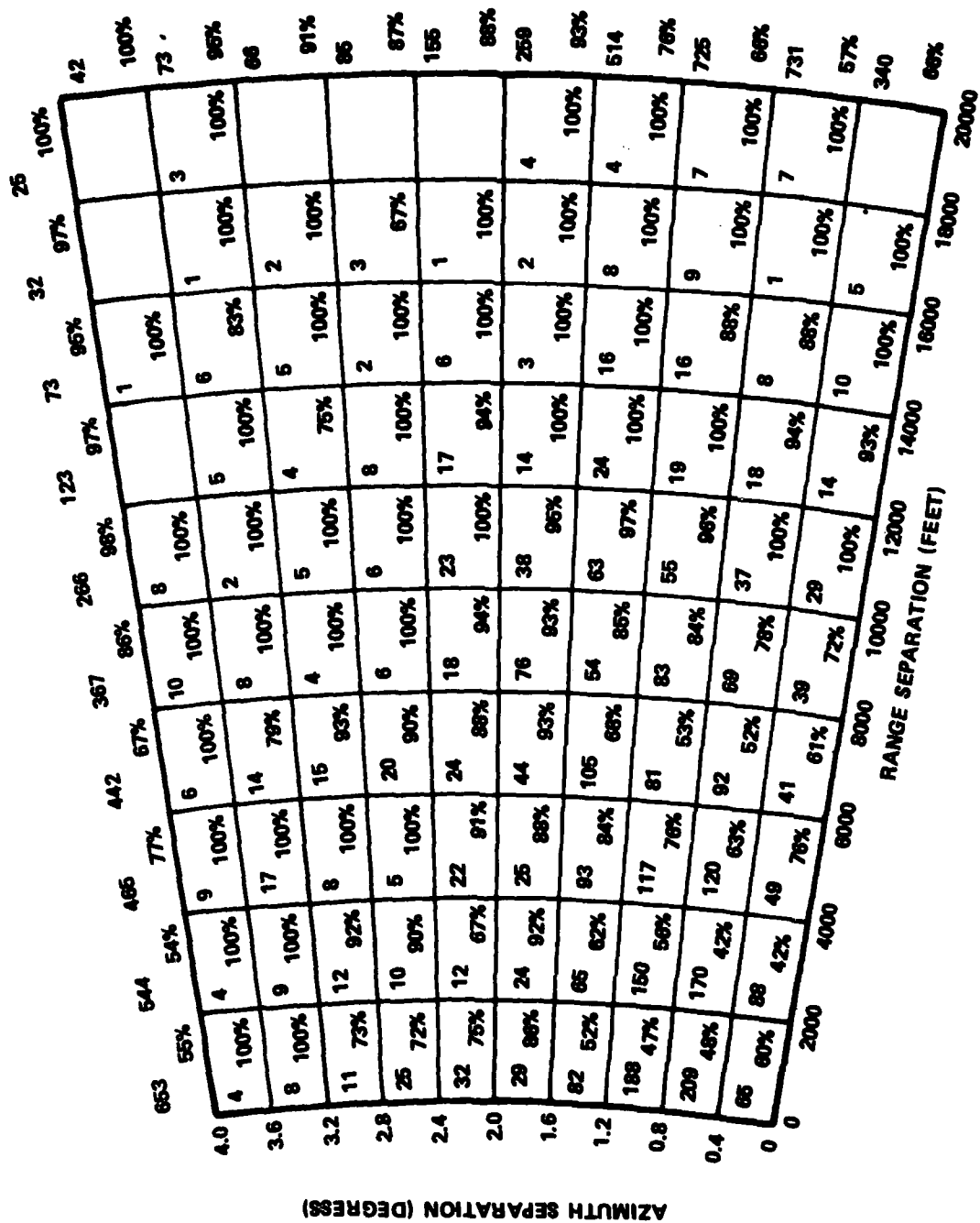
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FIGURE 5. AIRCRAFT BEACON RESOLUTION DATA — MODE S SENSOR CORRELATED REPORTS (0° TO 4° AZIMUTH AND 0 TO 20,000 FEET RANGE SEPARATION)



82-38-6

FIGURE 6. AIRCRAFT BEACON RESOLUTION DATA — MODE S CORRELATED AND UNCORRELATED REPORTS (0° TO 4° AZIMUTH AND 0 TO 20,000 FEET RANGE SEPARATION)



82-38-7

FIGURE 7. AIRCRAFT BEACON RESOLUTION DATA ARTS III TARGET REPORTS (0° TO 4° AZIMUTH AND 0 TO 20,000 FEET RANGE SEPARATION)

Since the collected aircraft separation data was not uniformly distributed, smaller separation groupings were analyzed to further insure the adequacy of the statistical results. Figure 8 illustrates the beacon resolution results for the Mode S correlated-only reports for a range separation interval every 1,000 feet from 0 to 10,000 feet, and an azimuth separation interval every 0.2° from 0° to 2° , yielding a 10 X 10 beacon resolution matrix. Figure 9 contains the results for the Mode S correlated and uncorrelated reports; figure 10 contains the results for the ARTS report.

Generally, the results follow the expected trend with the percentage resolved increasing as the range and/or azimuth separation increases. It is noticed that the resolution results vary as the range separation is increased from 0 to 10,000 feet in 1,000-foot increments. This is due to the potential bit conflicts for the particular A-Code used. However, as the azimuth separation increases, almost without exception, the beacon resolution percentage increases. A few exceptions to the trend exist, such as the 72 percent value for the Mode S correlated-only reports (see figure 8) for the 0.6° to 0.8° azimuth separation interval and the 0 to 1,000-foot range separation interval. The low 72 percent resolution value is caused by the distribution of samples in the interleaved versus bit conflict areas. Another anomaly in figure 7 shows that for 0 to 20,000-foot range separations, a higher percentage of resolved ARTS target reports (66 to 57 percent) occurred for the 0.0° to 0.4° separation interval than for the 0.4° to 0.8° separation interval. Exceptions, such as this one, were also caused by the sampling distribution in the interleaved versus the bit conflict areas. Other unexpected low percentages in figure 7 (such as the intervals from 16,000 to 18,000 feet and 2.4° to 2.8° or 6,000 to 8,000 feet and 3.2° to 3.6°) occur because of an insufficient sample size, or because the sample distribution contained an inordinately high percentage of samples in the bit conflict areas as compared to the overall percentage for the specific range separation interval. Similar unexpected values were contained in figures 5 through 10.

The effects of code bit conflicts on resolution results can be explained as follows:

Figure 11 illustrates the ATCRBS beacon code reply train for the specific beacon A-Codes, 0251 and 0252, used in the test program. When the two aircraft are separated by less than 0.45 microseconds or 221 feet, the A-Code 0251 reply conflicts with A-Code 0252 in seven of the bit positions. Figure 12 illustrates five conflicts where both bits are set: the F1, C1, C4, B2, and F2 pulses. There is a conflict involving the D1 pulse bit set for code 0251 and a conflict involving the D2 bit set for code 0252. When the aircraft are separated between 0.45 and 1.00 microseconds (221 and 492 feet, respectively), garbling conditions should not occur since the pulses from code 0252 do not overlap the pulses from code 0251. The areas where the pulses from the two codes cannot overlap are referred to as the interleaved areas. When the aircraft are separated between 1.00 and 1.90 microseconds (492 and 934 feet, respectively), the F1 pulse of the aircraft farther from the antenna overlaps the C1 pulse of the other aircraft creating a conflict with both overlapping bits set. With 1.45 microseconds (713 feet) of separation, the F1 pulse of the aircraft farther from the antenna directly overlaps C1 of the closer aircraft. This overlapping continues for another 0.45 to 1.90 microseconds (934 feet).

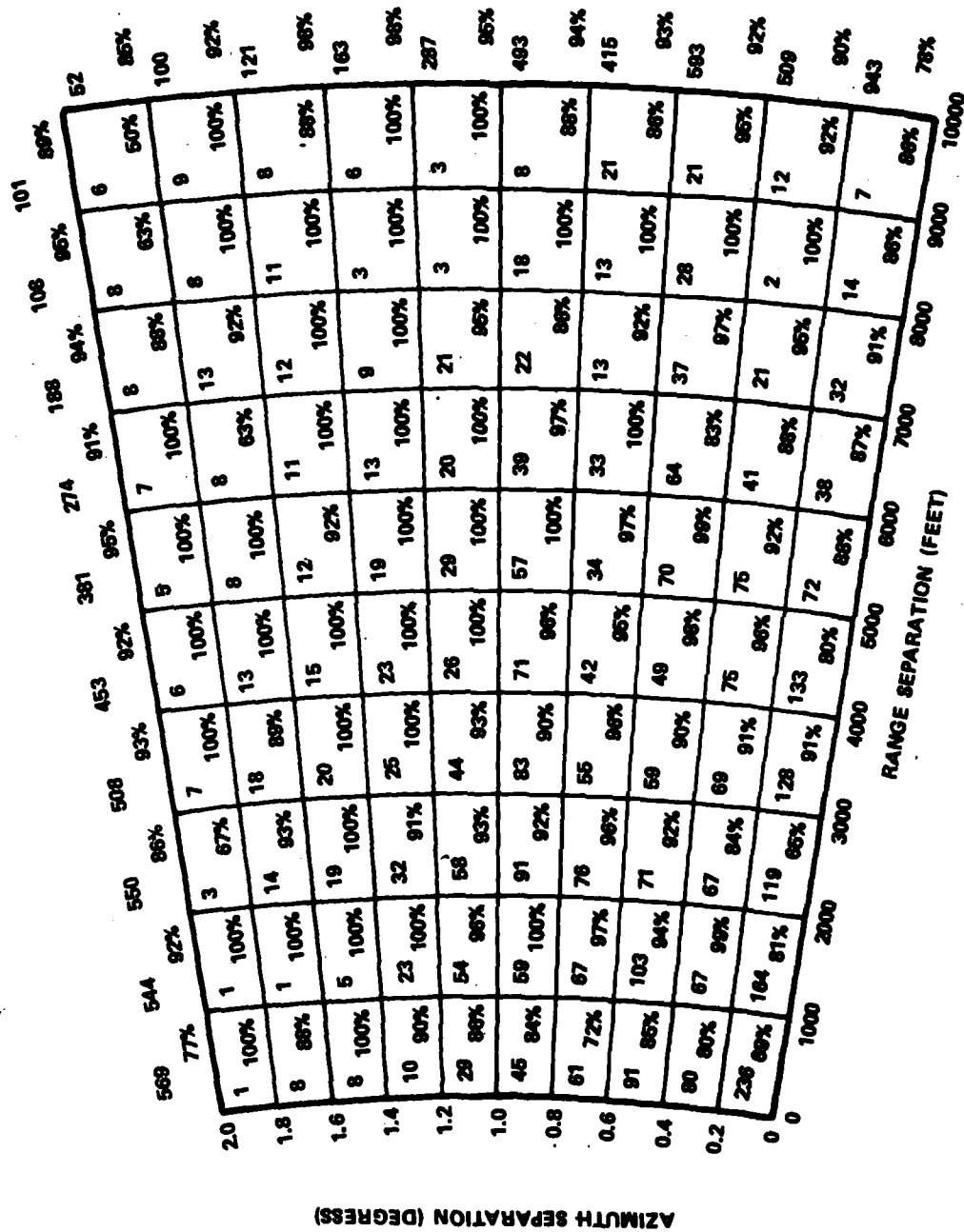


FIGURE 8. AIRCRAFT BEACON RESOLUTION DATA MODE S SENSOR CORRELATED REPORTS (0° TO 2° AZIMUTH AND 0 TO 10,000 FEET RANGE SEPARATION)

82-38-8

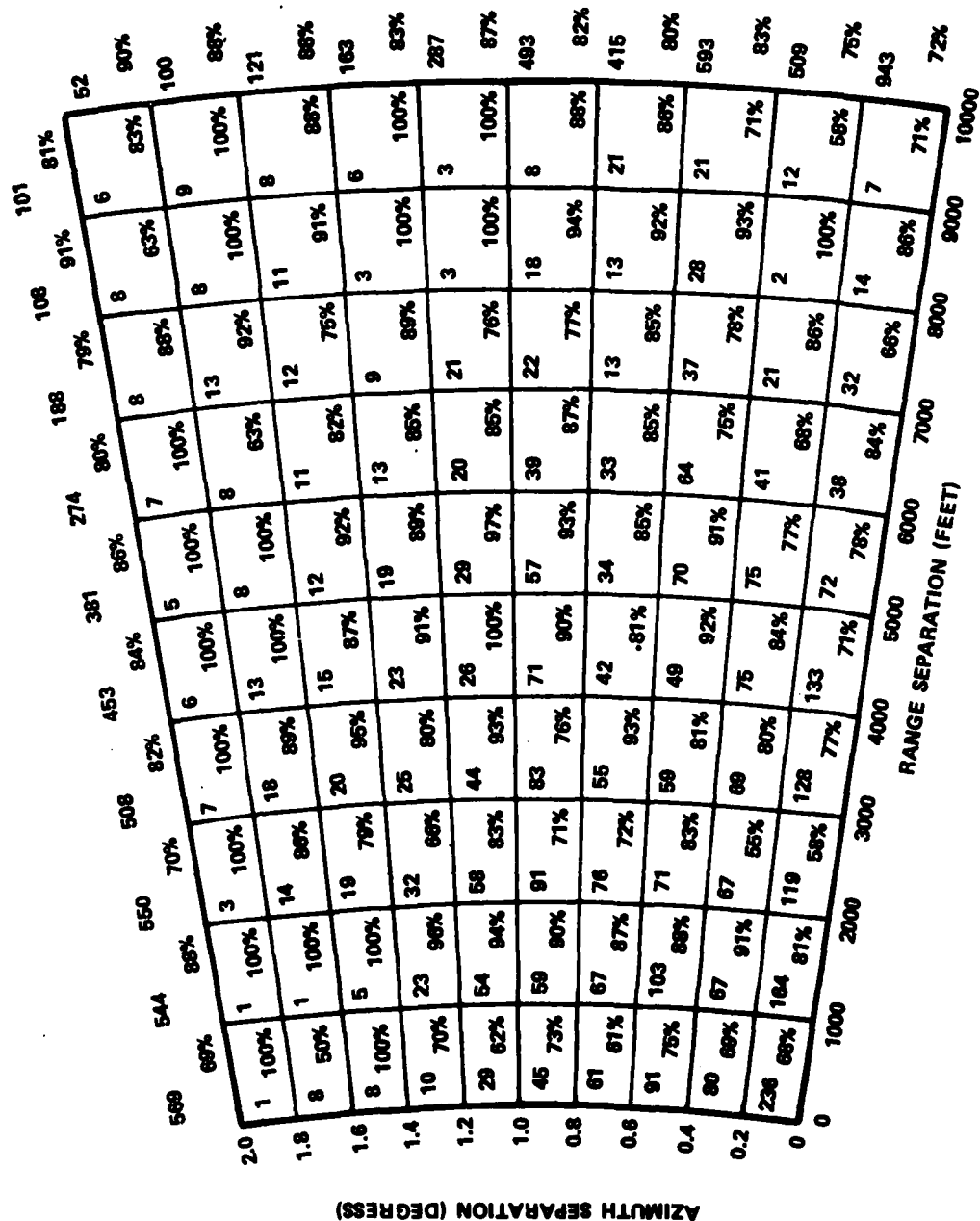
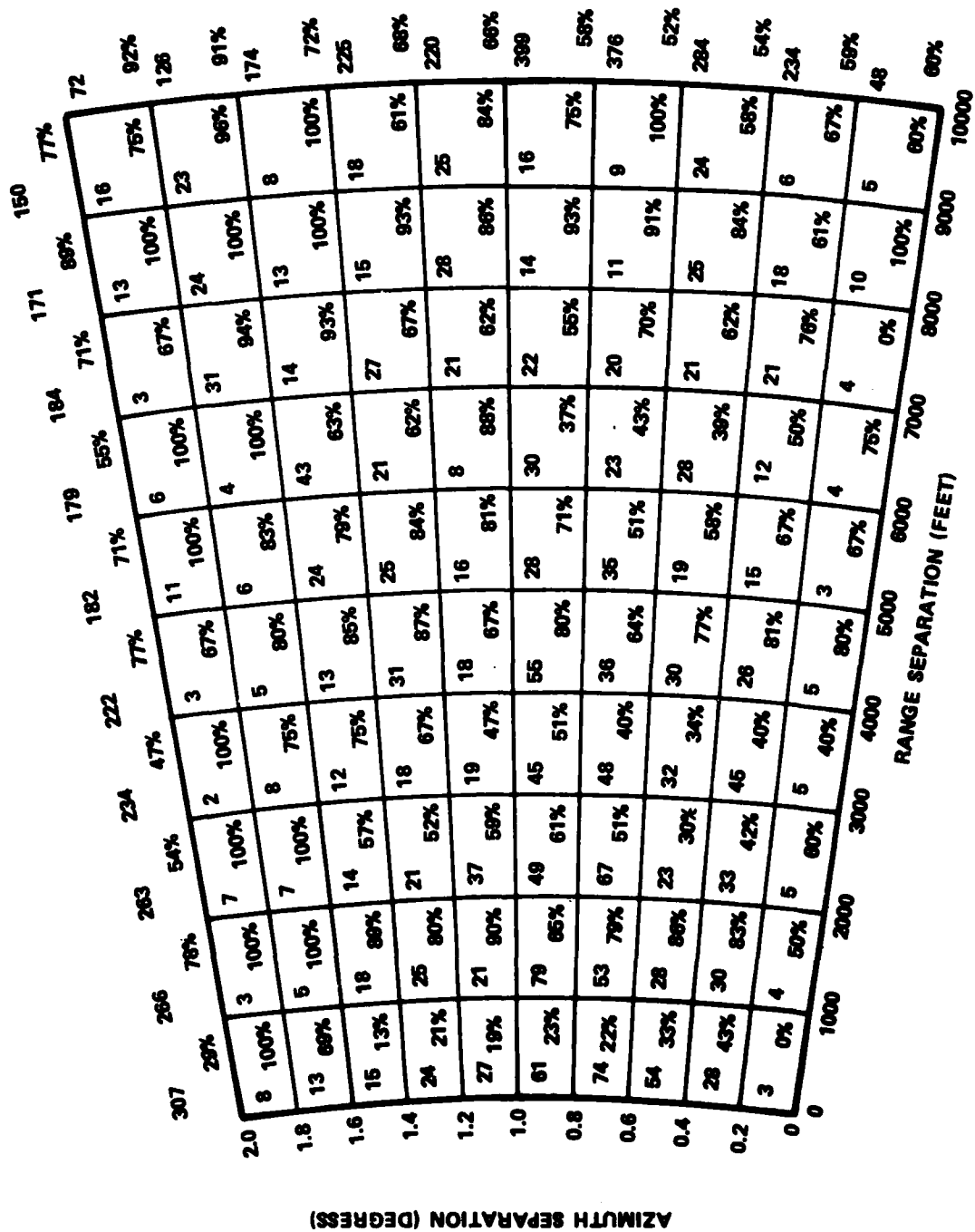
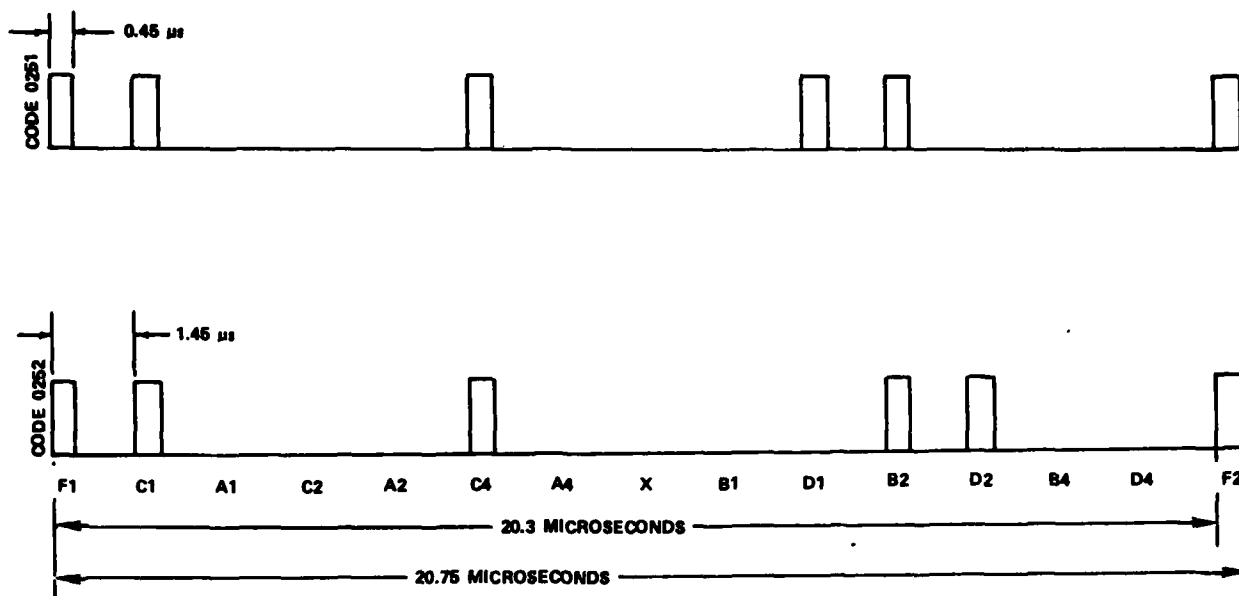


FIGURE 9. AIRCRAFT BEACON RESOLUTION DATA MODE S CORRELATED AND UNCORRELATED REPORTS (0° TO 2° AZIMUTH AND 0 TO 10,000 FEET RANGE SEPARATION)



82-38-10

FIGURE 10. AIRCRAFT BEACON RESOLUTION DATA ARTS 1:1 TARGET REPORTS (0° TO 2° AZIMUTH AND 0 TO 10,000 FEET RANGE SEPARATION)



PULSE WIDTHS ARE 0.45 MICROSECONDS = 221 FEET
 1.45 MICROSECONDS BETWEEN LEADING EDGES OF ADJACENT BITS = 713 FEET

82-38-11

FIGURE 11. REPLY SIGNAL FORMAT FOR ATCRBS A-CODES 0251 AND 0252

Figure 12 illustrates some relative bit position configurations, for A-Codes 0251 and 0252, for various aircraft range separations to illustrate the potential bit conflict conditions. Figure 12 assumes that the aircraft with A-Code 0252 is farther from the antenna. During the period between 1.00 and 1.90 microseconds of separation (492 and 934 feet, respectively), there exists one conflict where both the F1 pulse (code 0252) and the C1 pulse (code 0251) are sets. In addition, eight single bit conflicts result from the C4, D1, B2, and F2 bits of code 0251, and the C1, C4, B2, and D2 bits of code 0252.

For every different range separation between the two aircraft, a series of single and double bit conflicts can be computed. A detailed discussion of the effects of code bit conflicts for A-Codes 0251 and 0252 is contained in the appendix.

The analysis presented in the appendix indicates that a comparison of beacon resolution, or lack of resolution, in the bit-conflict areas versus the beacon resolution in the interleaved areas is dramatic: 99 percent versus 83 percent for the correlated only reports, and 98 percent versus 68 percent for the correlated and uncorrelated reports.

The type of bit conflicts (both bits set or only one bit set) also affects the resulting beacon resolution. In general, the fewer number of double bit conflicts, the better the beacon resolution. It can also be deduced that single bit conflicts do not adversely affect the resulting beacon resolution as much as double bit conflicts.

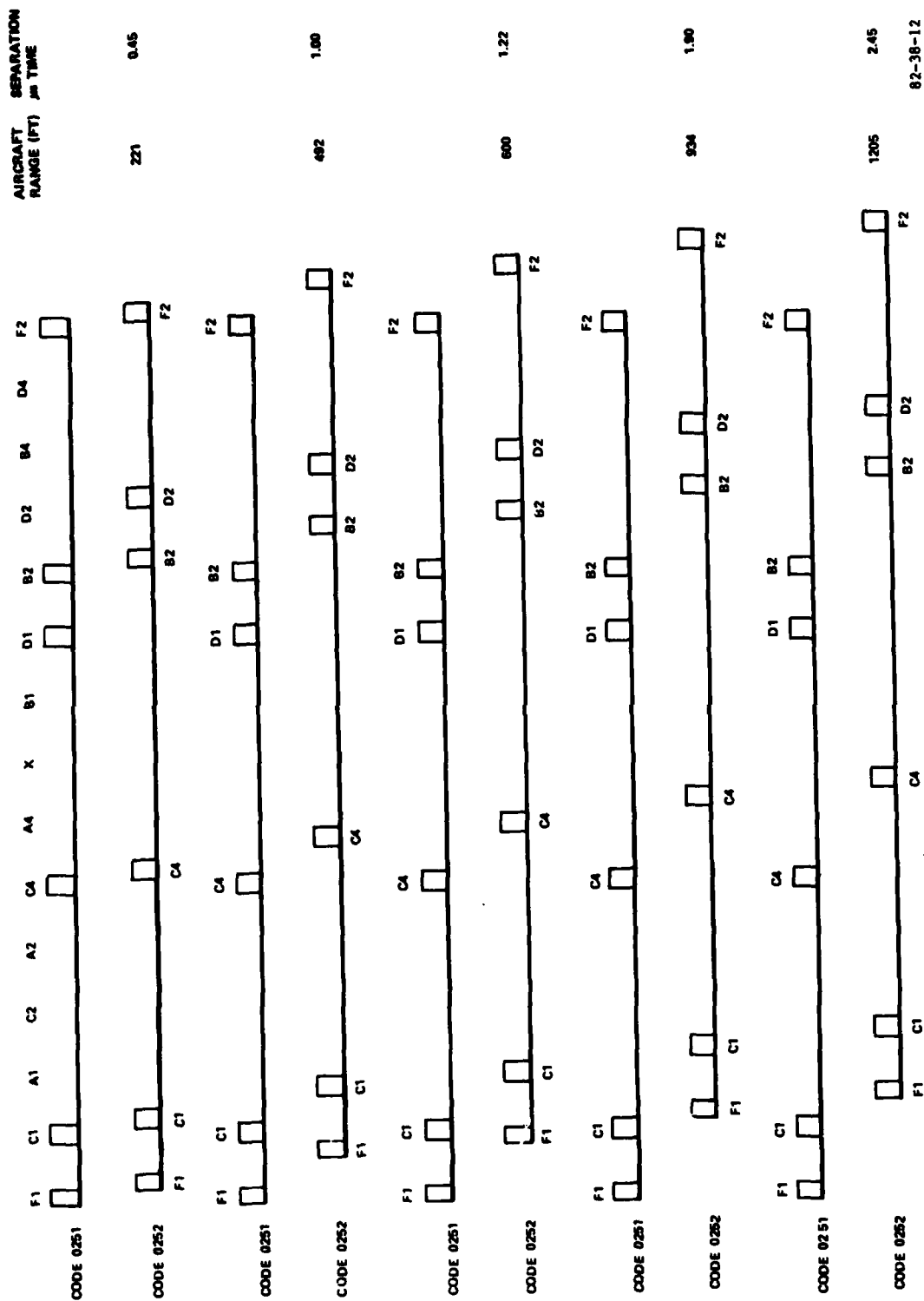


FIGURE 12. BIT POSITION CONFIGURATIONS FOR A-CODES 0251 AND 0252 FOR VARIOUS AIRCRAFT RANGE SEPARATIONS

The effect of double bit conflicts on beacon resolution, as compared to single bit conflicts, was empirically computed and found to be about five to six times as significant for correlated-only reports, and about ten times as significant for both correlated, and correlated and uncorrelated reports. A correlation analysis was performed on the data and it was found that the absolute correlation coefficient for both sets of Mode S data for double bit conflicts was greater than 0.80. On the other hand, the absolute correlation coefficient for both sets of Mode S data for single bit conflicts was less than 0.40. This further illustrates the greater significance of the double bit conflicts.

In summary: (1) bit-conflict areas have a significant affect on resulting beacon resolution, while interleaved areas have no affect; (2) the more bit conflicts (the smaller the slant range separation for these two codes), the poorer the beacon resolution; and (3) double bit conflicts more adversely affect the resulting beacon resolution than the single bit conflicts.

In any event, the minimum achievable separation between two aircraft, with no garbling, is approximately 10,000 feet in range and/or 2° in azimuth for the Mode S, and 3.2° in azimuth for the ARTS. Consequently, for the beacon resolution comparison of the Mode S and ARTS, only those reports with aircraft separation of 0 to 10,000 feet in range and 0° to 2° in azimuth are considered. This area of consideration is presented in figure 8, and those data are discussed in the subsequent beacon resolution comparison.

MODE S VERSUS ARTS III BEACON RESOLUTION COMPARISON.

Table 1 illustrates the overall comparison results of beacon resolution between the Mode S sensor (correlated only, and correlated and uncorrelated reports) and the ARTS III. This overall comparison is for the entire range separation interval of 0 to 10,000 feet and the entire azimuth separation interval of 0° to 2°. These composite results show that both Mode S dissemination options were superior to the ARTS III target reports. The correlated only reports processed by the Mode S sensor were resolved 89 percent of the time. The Mode S sensor's correlated and uncorrelated reports were resolved 80 percent of the time, and the ARTS III reports were resolved only 62 percent of the time.

TABLE 1. COMPARISON OF OVERALL BEACON RESOLUTION RESULTS FROM THE MODE S SENSOR AND THE ARTS III

Azimuth Interval (degrees) Slant Range Interval (feet)	<u>Aircraft Separation</u>	
	0 to 2	0 to 10,000
	<u>Sample Sizes</u>	<u>Resolution (Percent Resolved)</u>
Mode S Correlated-Only Reports	3,676	89
Mode S Correlated and Uncorrelated Reports	3,676	80
ARTS III Reports	2,158	62

As expected, the Mode S sensor's correlated reports provided better beacon resolution than the combined correlated and uncorrelated Mode S reports for the entire separation interval. The internal Mode S sensor logic, which is performed on the correlated reports prior to ATC dissemination, accounts for the improved beacon resolution over the uncorrelated reports. Consequently, correlated-only beacon resolution is superior to the combined correlated and uncorrelated results.

Figure 13 summarizes the overall performance of the three systems tested and provides a 5 x 5 aircraft separation matrix of the area of consideration. Each of the 25 cells contains six numbers. The three top numbers, from left to right, represent the sample sizes for the Mode S correlated-only reports, the Mode S correlated and uncorrelated reports, and the ARTS reports, respectively. The bottom three numbers represent, from left to right, the resulting beacon resolution percentages for the Mode S correlated-only reports, the Mode S correlated and uncorrelated reports, and the ARTS reports, respectively.

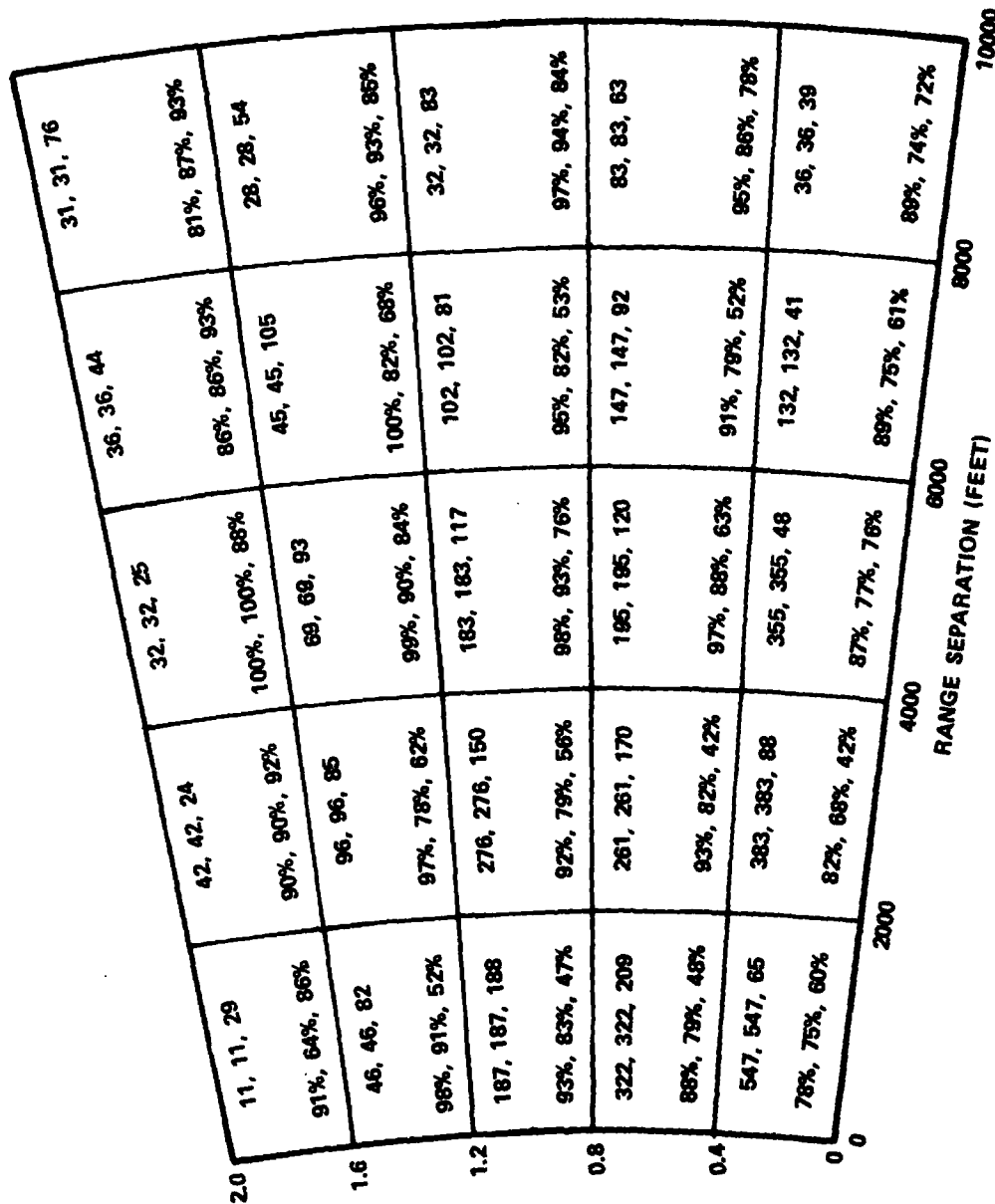
The Mode S correlated-only reports provided better beacon resolution results than the ARTS in 22 of the 25 aircraft separation cells. The Mode S correlated and uncorrelated reports provided better beacon resolution results than the ARTS in 21 of the 25 separation cells. In addition, the Mode S correlated-only reports provided better resolution than the Mode S correlated and uncorrelated reports in 21 of the 25 separation cells with three ties.

In general, the percentage resolved increases as the range and/or the azimuth separation increases. As the range separation increases, there are less bits overlapping and, consequently, less garbling. As the azimuth separation increases, the two aircraft have less chance of appearing in the same antenna beamwidth. Once one of the aircraft is outside of the beam, the possible garbling condition subsides.

SUMMARY OF RESULTS

1. The minimum achievable separation between two ATCRBS equipped aircraft with no garbling is approximately 10,000 feet range separation or 2° azimuth separation for the Mode S system, and 10,000 feet range separation or 3.2° azimuth separation for the ARTS.
2. The resulting ATCRBS beacon resolution for the Mode S correlated reports is 89 percent resolved for the 0° to 2° azimuth separation interval and the 0 to 10,000 feet range separation interval.
3. The resulting ATCRBS beacon resolution for the Mode S sensor combined correlated and uncorrelated reports is 80 percent resolved for the 0° to 2° azimuth separation interval and the 0 to 10,000 feet range separation interval.
4. The resulting beacon resolution for the ARTS III reports is 62 percent resolved for the 0° to 2° azimuth separation interval and the 0 to 10,000 feet range separation interval.
5. It was empirically determined from the data (see the appendix) that double-bit (both bits set) conflicts adversely affect beacon resolution 10 times as much as single-bit (one bit set) conflicts for the Mode S correlated and uncorrelated reports.

AZIMUTH SEPARATION (DEGREES)



82-38-13

FIGURE 13. AIRCRAFT BEACON RESOLUTION DATA COMPARISON AMONG MODE S CORRELATED, MODE S CORRELATED PLUS UNCORRELATED, AND ARTS III REPORTS (0° TO 2° AZIMUTH AND 0 TO 10,000 FEET RANGE SEPARATION)

CONCLUSIONS

1. The Mode S correlated reports consistently provide better Air Traffic Control Radar Beacon System (ATCRBS) beacon resolution results than the Mode S correlated and uncorrelated reports.
2. The Mode S is susceptible to ATCRBS beacon code garbling whenever the aircraft azimuth separation is less than 2°. The Automated Radar Terminal System (ARTS) is susceptible to ATCRBS beacon code garbling whenever the aircraft azimuth separation is less than 3.2°.

RECOMMENDATION

Disseminate Mode S correlated-only reports to air traffic control facilities when maximum beacon code resolution is required.

REFERENCES

1. M. Holtz, et al., Discrete Address Beacon System (DABS) Baseline Test and Evaluation, FAA-RD-80-36, April 1980.
2. Drouilhet, P. R., DABS: A System Description, Lincoln Laboratory, MIT Project ATC-42, FAA-RD-74-189, November 18, 1974.
3. Orlando, V. A. and Drouilhet, P. R., Discrete Address Beacon System Functional Description, Lincoln Laboratory, MIT Project ATC-42A, FAA-RD-80-41, April 1980.
4. Luciani, V. J., NAFEC Range Instrumentation Systems, FAA-NA-79-32, February 1980.

APPENDIX

The purpose of the appendix is to analyze the bit-by-bit garbling effects of the two specific A-Codes (0251 and 0252) used throughout the beacon resolution testing. Specifically, the significance of the bit-conflict and interleaved areas are investigated. In addition, the significance, or difference in significance, of bit conflicts of the type where only one of the conflicting bits are set, is compared to the type where both of the conflicting bits are set. The analysis is done for the Mode S correlated-only, and the Mode S correlated and uncorrelated reports. The Automated Radar Terminal System (ARTS) reports were not analyzed for bit-by-bit garbling because the ARTS system is not automatically time synchronized to the time standard, WWVB. Even though the ARTS was manually time-synchronized to WWVB, and the expected error is no more than 0.5 second (approximately 40 feet range separation), time intervals in the order of 0.45 microseconds (221 feet) are investigated and the 40-foot error could be significant. Therefore, only the Mode S reports are analyzed bit-by-bit.

The specific beacon A-Codes, 0251 and 0252, were used in this test program. When the two aircraft are separated by less than 0.45 microseconds or 221 feet, the A-Code 0251 reply conflicts with A-Code 0252 in seven of the bit positions. Figure 12 (in the main text) illustrates five conflicts (F1, C1, C4, B2, and F2 pulses) where both bits are set. There is a conflict involving the D1 pulse bit set for code 0251 and a conflict involving the D2 bit set for code 0252. When the aircraft are separated between 0.45 and 1.00 microseconds (221 and 492 feet, respectively), garbling conditions should not occur since the pulses from code 0252 do not overlap the pulses from code 0251. The areas where the pulses from the two codes cannot overlap are referred to as the interleaved areas. When the aircraft are separated between 1.00 and 1.90 microseconds (492 and 934 feet, respectively), the F1 pulse of the aircraft farther from the antenna overlaps the C1 pulse of the other aircraft, creating a conflict with both overlapping bits set. With 1.45 microseconds (713 feet) of separation, the F1 pulse of the aircraft farther from the antenna directly overlaps C1 of the closer aircraft. This overlapping continues for another 0.45 to 1.90 microseconds (934 feet).

Figure 12 illustrates some relative bit position configurations, for A-Codes, 0251 and 0252, for various aircraft range separations to illustrate the potential bit conflict conditions. Figure 12 assumes that the aircraft with A-Code 0252 is farther from the antenna. During the period between 1.00 and 1.90 microseconds (492 and 934 feet, respectively) of separation, there exists one conflict where both the F1 pulse (code 0252) and the C1 pulse (code 0251) are sets. In addition, eight single bit conflicts result from the C4, D1, B2, and F2 bits of code 0251, and the C1, C4, B2, and D2 bits of code 0252. Figure A-1 illustrates all possible bit overlapping situations, assuming that the aircraft with A-Code 0252 is farther from the antenna. A one indicates that the particular bit is set; a zero indicates an unset condition. Figure A-2 is analogous to figure A-1, with the reverse assumption that the aircraft with A-Code 0252 is closer to the antenna. The range separation intervals of figure A-1 and A-2 reflect the possible bit conflicts, stating the number of overlaps with both bits set as well as only one bit set. Theoretically, the garbling of beacon codes should not occur at range separations that are not specified as conflict areas (the interleaved areas).

The beacon resolution flights were conducted such that the overtaking aircraft, which was positioned closer to the antenna, commenced its flightpath about 2 nautical miles (nmi) behind the target aircraft on the outbound leg. The overtaking aircraft overtook the target aircraft midway through the outbound leg, and finished about 2 nmi ahead of the target aircraft. The inbound legs of the flights are a mirror image of the outbound legs. Since the overtaking aircraft is farther from the antenna, about 50 percent of each leg (both outbound and inbound), the conflict occurrences shown in figures A-1 and A-2 were averaged; the averaged values are displayed in table A-1.

The Mode S beacon resolution data were sorted into a 10 x 30 matrix according to the azimuth and range separation of the two aircraft. The azimuth separation was categorized into 10 bins from 0° to 2° in 0.2° increments. The range separation was sorted into 30 bins using the appropriate range increments from table A-2. The percentage resolved and the number of samples are denoted for each of the 100 cells and are displayed in figures A-3 through A-8. A blank area indicates that no samples were taken in that cell. Figures A-3, A-4, and A-5 reflect Mode S correlated-only reports. Figures A-6, A-7, and A-8 reflect Mode S correlated and uncorrelated reports. Each 10 x 10 figure represents one-third of its respective 10 x 30 matrix.

Figures A-3 through A-8 were analyzed in conjunction with the 15 interleaved areas. The 15 even numbered range cells reflect range separation in the interleaved areas, which should, theoretically, be void of garbling interference. Both sets of Mode S reports (correlated-only, and correlated and uncorrelated) show virtually no garbling difficulties in these 15 interleaved range bins, as displayed in figures A-3 through A-8. The percentage resolved for both correlated-only and correlated and uncorrelated reports in the interleaved areas varied from 96 to 100 percent (weighted percentages at the top of the figures A-3 through A-8, for the even-numbered bins). The overall weighted average was 99 percent for the correlated-only reports; the overall weighted average was 98 percent for the correlated and uncorrelated reports. These overall averages represent a weighted average from the 15 interleaved areas.

Table A-1 summarizes the beacon resolution results for the 15 bit conflict areas. It should be noted that these resolution percentages were obtained directly from figures A-3 through A-8. The percentages resolved for both correlated only and correlated and uncorrelated reports in the bit-conflict areas, varied from only 40 to 100 percent (weighted percentage at the top of figures A-3 through A-8, for the 15 odd-numbered bins). The overall weighted average was 83 percent for correlated-only reports; the overall weighted average was 68 percent for the correlated and uncorrelated reports. These overall averages represent a weighted average from the 15 bit-conflict areas.

The comparison of beacon resolution, or lack of resolution, in the bit-conflict areas versus the beacon resolution in the interleaved areas is dramatic: 99 versus 83 percent for the correlated-only reports and 98 percent versus 68 percent for the correlated and uncorrelated reports.

The type of bit conflicts (both bits set or only one bit set) will also affect the resulting beacon resolution. A review of table A-1 indicates that, in general, the fewer number of double bit conflicts, the better the beacon resolution. It can also be deduced that single bit conflicts do not adversely affect the resulting beacon resolution as much as double bit conflicts.

The effect of double bit conflicts on beacon resolution, as compared to single bit conflicts, was empirically computed and found to be about five to six times as significant for correlated-only reports, and about ten times as significant for both correlated and uncorrelated reports. A correlation analysis was performed on the data and it was found that the absolute correlation coefficient for both sets of Mode S data for double bit conflicts was greater than 0.80. On the other hand, the absolute correlation coefficient for both sets of the Mode S data for single bit conflicts was less than 0.40. This further illustrates the greater significance of the double bit conflicts.

In summary: (1) bit-conflict areas have a significant affect on resulting beacon resolution, while interleaved areas have no affect; (2) the more bit conflicts (the smaller the slant range separation for these two codes), the poorer the beacon resolution; and (3) double bit conflicts more adversely affect the resulting beacon resolution than the single bit conflicts.

TABLE A-1. PERCENTAGE RESOLVED FOR RANGE SEPARATIONS WHERE CODE OVERLAPPING EXISTS

Aircraft Range Separation (ft)	Average Number of Conflicts		Percentage Resolved	
	<u>Both Bit Set</u>	<u>Both Bit Set</u>	<u>Mode S Correlated Reports</u>	<u>Mode S Correlated and Uncorrelated Reports</u>
0-221	5	2	44	40
492-934	2	6	79	61
1205-1647	0.5	8	84	74
2928-2360	0.5	8	86	71
2631-3073	2.5	3.5	81	60
3344-3786	2.5	2.5	83	60
4057-4499	0.5	5	84	70
4770-5212	0	6	98	90
5483-5925	0.5	5	90	73
6196-6638	2.5	1	81	59
6909-7351	1.5	1.5	90	72
7622-8065	0.5	2.5	96	75
8335-8778	0	3	91	81
9048-9491	0.5	2	80	60
9761-10204	1	0.5	97	100

		Range Conflict Areas																Aircraft Range Separation (ft)*	Average Number of Conflicts	
		Code 0252 Airplane Exceeds Code 0251 Airplane in Slant Range																	Both Bits Set	One Bit Set
		F1	C1	A2	C2	A2	C4	A4	X	B1	D1	B2	D2	B4	D4	F2				
Code 0251	1	1	0	0	0	1	0	0	0	1	1	0	0	0	0	1	0-221	5	2	
Code 0252	1	1	0	0	0	1	0	0	0	1	1	0	0	1	0	0	492-934	1	8	
		1	1	0	0	0	1	0	0	0	0	1	1	0	0	0	1205-1647	0	9	
				1	1	0	0	0	1	0	0	0	0	1	1	1	2928-2360	1	7	
						1	1	0	0	1	0	0	0	0	0	1	2631-3073	3	2	
							1	1	0	0	0	1	0	0	0	0	3344-3786	2	3	
								1	1	0	0	0	1	0	0	0	4057-4499	0	6	
									1	1	0	0	0	1	0	0	4770-5212	0	6	
										1	1	0	0	0	1	0	5483-5925	1	4	
											1	1	0	0	0	1	6196-6638	3	0	
												1	1	0	0	0	6909-7351	1	2	
													1	1	0	0	7622-8065	0	3	
														1	1	0	8335-8778	0	3	
															1	1	9048-9491	1	1	
																1	9761-10204	1	0	

*All slant range separations between 0 to 10,204 feet, other than those specified, have no bit conflicts and are referred to as interleaved area.

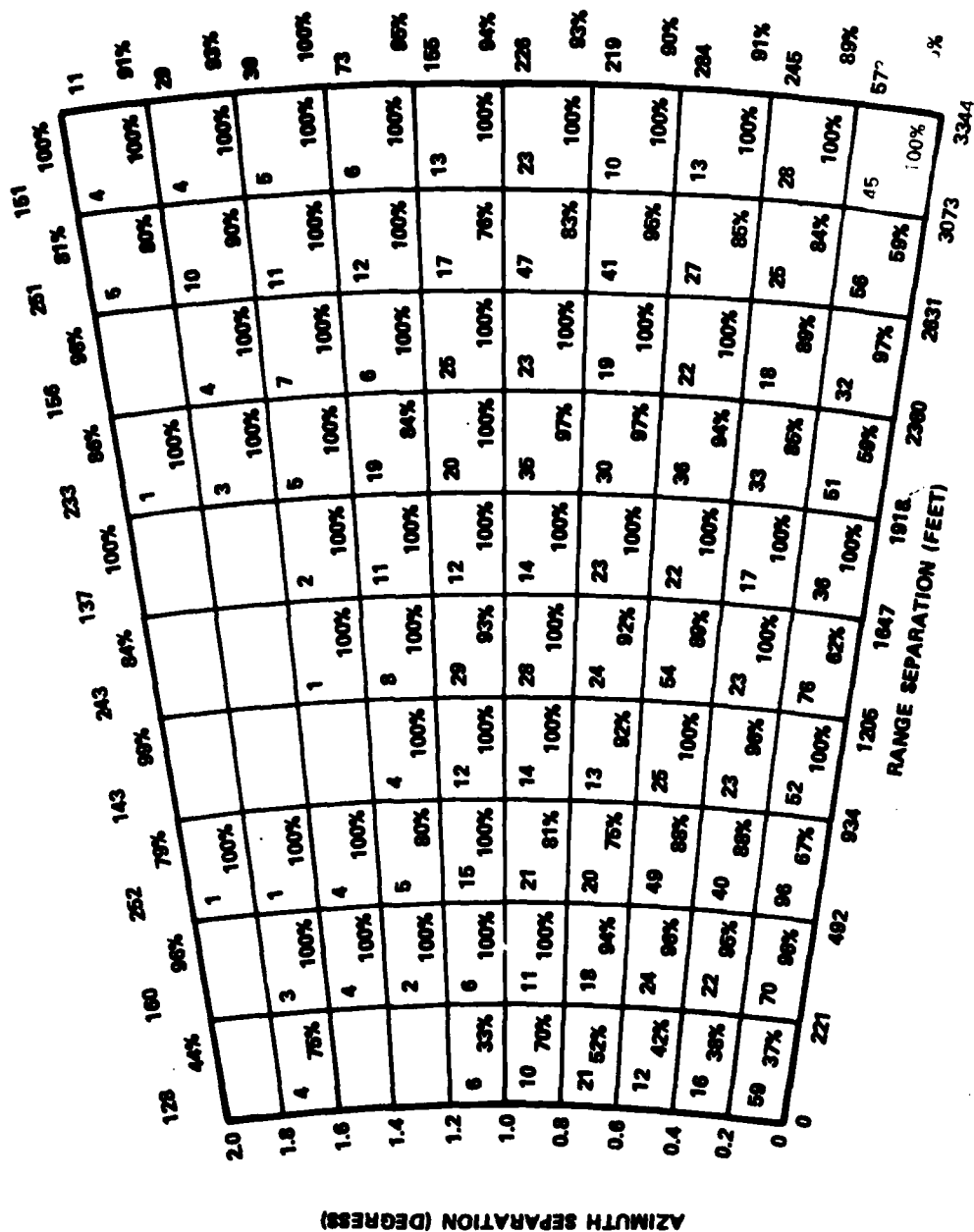
FIGURE A-1. RANGE CONFLICT AREAS WHEN CODE 0252 AIRPLANE EXCEEDS CODE 0251 AIRPLANE IN SLANT RANGE

Range Conflict Areas																	Aircraft Range Separation (ft)*	Average Number of Conflicts	
Code 0251 Airplane Exceeds Code 0252 Airplane in Slant Range																		Both Bits Set	One Bit Set
	F1	C1	A1	C2	A2	C4	A4	X	B1	D1	B2	D2	B4	D4	F2				
Code 0252	1	1	0	0	0	1	0	0	0	0	1	1	0	0	1		0-221	5	2
Code 0251	1	1	0	0	0	1	0	0	0	1	1	0	0	0	1		492-934	3	4
		1	1	0	0	0	1	0	0	0	1	1	0	0	0		1205-1647	1	7
			1	1	0	0	0	1	0	0	0	0	1	1	0		2928-2360	0	9
				1	1	0	0	0	1	0	0	0	0	1	1		2631-3073	2	5
					1	1	0	0	0	1	0	0	0	0	1		3344-3786	3	2
						1	1	0	0	0	1	0	0	0	0		4057-4499	1	4
							1	1	0	0	0	0	1	0	0		4770-5212	0	6
								1	1	0	0	0	0	0	1		5483-5925	0	6
									1	1	0	0	0	0	1		6196-6638	2	2
										1	1	0	0	0	0		6909-7351	2	1
											1	1	0	0	0		7622-8065	1	2
													1	1	0		8335-8778	0	3
															1		9048-9491	1	1
																	9761-10204	1	0

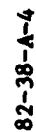
*All slant range separations between 0 to 10,204 feet, other than those specified, have no bit conflicts and are referred to as interleaved area.

FIGURE A-2. RANGE CONFLICT AREAS WHEN CODE 0251 AIRPLANE EXCEEDS CODE 0252 AIRPLANE IN SLANT RANGE

AIRCRAFT BEACON RESOLUTION DATA
MODE S SENSOR CORRELATED REPORTS



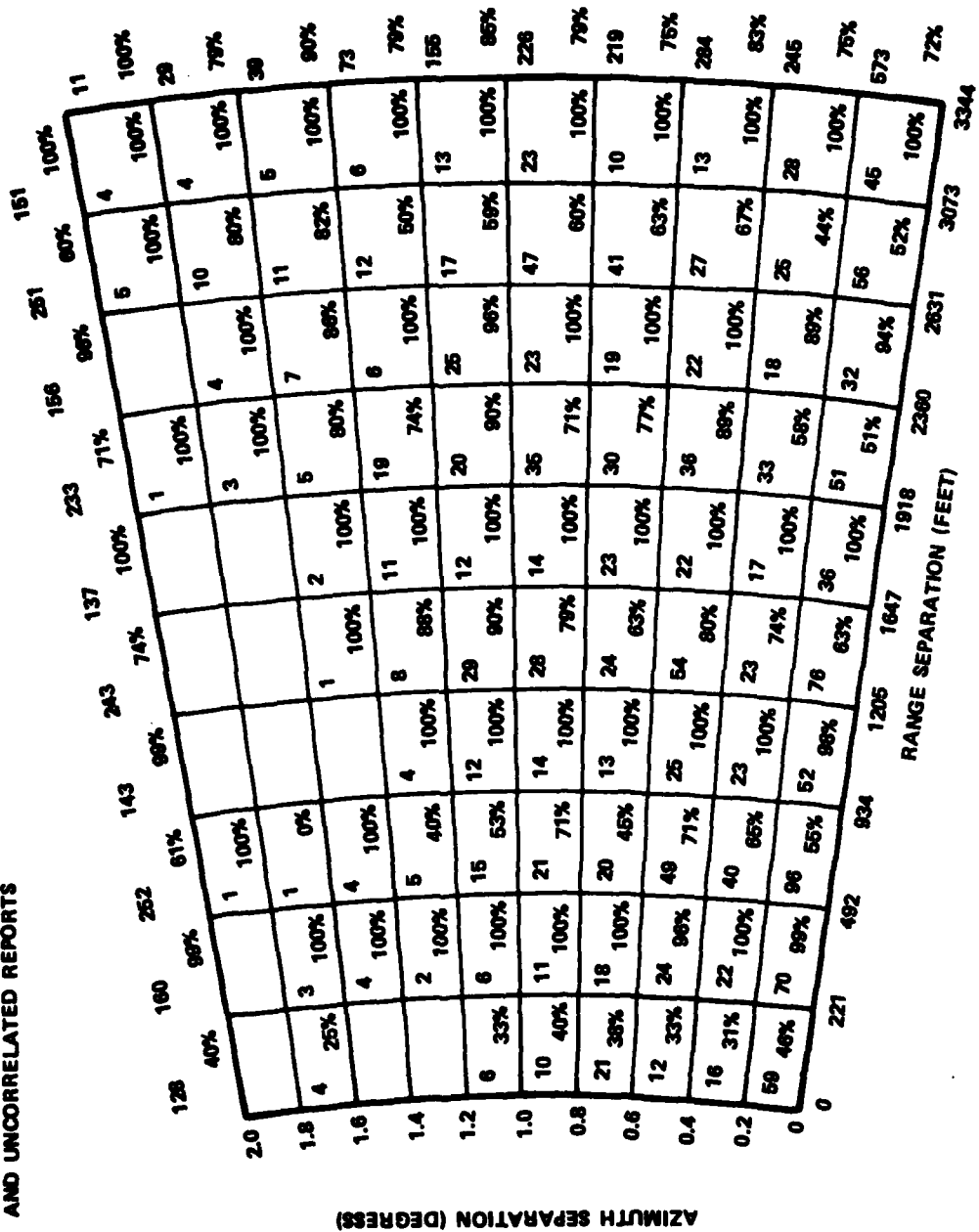
AZIMUTH SEPARATION (DEGREES)



AZIMUTH SEPARATION (DEGREES)		RANGE SEPARATION (FEET)															
		6809	7351	7622	8065	8335	8776	9048	9491	9761	10204	10474	10804	11134	11464	11794	
2.0	3 100%	3 100%	3 100%	3 33%	1 100%	4 50%	3 100%	4 100%	3 100%	4 50%	3 67%	1 100%	25 100%	33 97%	41 100%	49 100%	
1.8	8 75%	3 100%	3 100%	3 100%	3 100%	3 100%	3 100%	4 100%	2 100%	4 50%	4 100%	2 100%	34 94%	42 100%	50 100%	58 100%	
1.6	4 100%	1 100%	10 100%	4 100%	4 100%	6 100%	2 100%	2 100%	2 100%	2 50%	2 100%	2 100%	33 97%	41 100%	49 100%	57 100%	
1.4	3 100%	3 100%	4 100%	4 100%			3 100%	3 100%	3 100%	3 100%	3 100%	2 100%	21 100%	29 100%	37 100%	45 100%	
1.2	10 80%	6 100%	7 100%	1 100%	1 100%	2 100%					1 100%	1 100%	32 97%	40 100%	48 100%	56 100%	
1.0	12 83%	8 88%	8 100%	6 100%	7 100%	7 100%	3 100%	2 50%	4 100%	5 100%	3 100%	3 100%	58 93%	66 100%	74 100%	82 100%	
0.8	13 92%	1 100%	3 100%	1 100%	7 100%	7 100%	6 100%	9 78%	7 86%	3 100%	1 100%	1 100%	51 92%	59 100%	67 100%	75 100%	
0.6	21 95%	13 100%	9 100%	9 100%	11 100%	11 100%	7 100%	11 91%	7 100%	4 100%	1 100%	1 100%	93 98%	101 100%	109 100%	117 100%	
0.4	7 100%	5 100%	10 90%	2 100%			1 100%	7 86%	2 100%	3 100%	2 100%	2 100%	80 96%	88 100%	96 100%	104 100%	
0.2	18 83%	7 100%	12 100%	3 100%	7 100%	7 71%	4 100%	3 67%	2 100%	2 100%	2 100%	2 100%	60 90%	68 100%	76 100%	84 100%	
0	6809	7351	7622	8065	8335	8776	9048	9491	9761	10204	10474	10804	11134	11464	11794	12124	

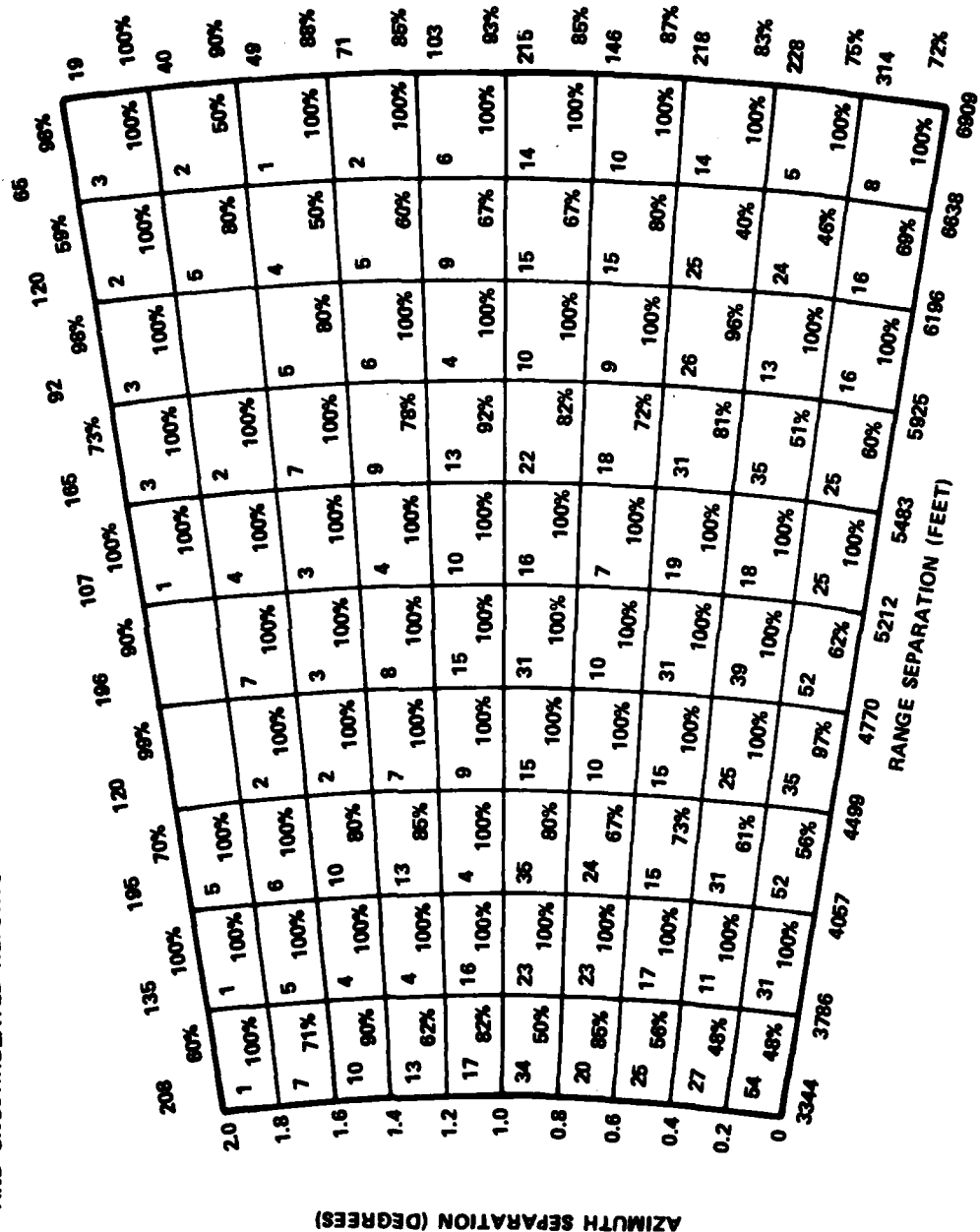
A-9

AIRCRAFT BEACON RESOLUTION DATA
MODE S SENSOR CORRELATED REPORTS
AND UNCORRELATED REPORTS



82-38-A-6

AIRCRAFT BEACON RESOLUTION DATA
MODE S SENSOR CORRELATED REPORTS
AND UNCORRELATED REPORTS



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AIRCRAFT BEACON RESOLUTION DATA
MODE S SENSOR CORRELATED REPORTS
AND UNCORRELATED REPORTS

AZIMUTH SEPARATION (DEGREES)	RANGE SEPARATION (FEET)											
	6809	7351	7622	8065	8335	8778	9048	9491	9761	10204	10474	
100	72%	96%	75%	100%	81%	100%	45	27	96%	100%	100%	25
2.0	3	3	3	1	4	3	4	4	3	1	1	13
1.8	3	3	3	3	3	2	4	2	4	2	2	33
1.6	8	3	3	10	6	2	2	2	100%	100%	100%	25
1.4	4	1	1	4	100%	83%	100%	50%	100%	100%	2	34
1.2	3	3	3	4	75%	3	3	100%	100%	100%	100%	94%
1.0	10	6	7	1	2	100%	100%	100%	100%	100%	100%	33
0.8	12	8	8	6	7	86%	100%	50%	100%	100%	100%	86%
0.6	13	1	3	1	7	86%	100%	78%	86%	100%	100%	21
0.4	21	13	9	9	11	82%	100%	45%	100%	100%	100%	95%
0.2	7	5	10	2	1	7	100%	28%	100%	100%	100%	32
0	19	7	12	3	7	71%	100%	33%	100%	100%	100%	84%
	6809	7351	7622	8065	8335	8778	9048	9491	9761	10204	10474	58

82-38-A-8

DATE
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